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A comprehensive study on lithium-ion battery management system

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ABSTRACT
The charging current, discharge rate, discharge limit and operating temperature are sensitive matters in LIBs. Economic losses of high magnitude also arise from collapse of battery bank due to single weak battery which has been charged/discharged repeatedly beyond safe operating limit. Implication of Peukert effect on real batteries is investigated. It can be deduced that as current approaches a very low level, the actual battery capacity appreciates considerably beyond its rated capacity. On the contrary, when this behavior is balanced with self-discharge of the battery, the effect cancels out. The result also revealed that a 200Ah battery discharged at the rate of 1A will last for 355 days 39 minutes which is about 15 days; during this time, a typical deep cycle would have self-discharged 15 to 20 amperes. This concludes that Peukert's effect is veritable at all discharge rates of a battery (high and low levels) and this effect is partially as a result of slow electrolyte diffusion and partially a result of an internal resistance that varies as a function of discharge rate. This makes the calculation and measurement of battery parameters more intricate and convoluted for most SOC meter designers.

1. INTRODUCTION
Lithium ion (Li-ion) Batteries (LIBs) is the most sought after rechargeable batteries, and have been widely used to power small electronic devices, portable tools, hybrid and electrical vehicles. These batteries are able to provide energy by moving lithium ions

from anode to cathode, whereas during charge, these lithium ions are forced back to the anode from cathode. Taking lithium cobalt battery which is a type of LIBs as an example, the reactions happen at both anode and cathode as shown in equations 1.0 and 2.0 respectively. The overall electrochemical reaction is shown in (2.3) (Bergveld *et al*, 2002).

$LiCoO_2 \rightleftarrows Li_{1-x}CoO_2 + xLi^+ + xe^-$ (Anode) 1.0

$xLi^+ + xe^- + 6C \rightleftarrows Li_xC_6$ (Cathode) 2.0

$Li^+ + LiCoO_2 \quad Li_2O + CoO$ (Overall) 3.0

The numerous advantages of LIBs over other batteries are longer lifetime, no memory effect, higher energy density, longer shelf time and lower self-discharge rate (Clean Energy Institute, 2019). However, they also have certain disadvantages such as temperature limitations, high cost, low overcharge/high voltage tolerance, and related safety issues (Battery University, 2010). Lead-acid battery has the lowest energy density of rechargeable cells, making it unsuitable for smaller consumer electronics (Buchmann, 2011). LIBs are susceptible to explosion when exposed to overcharge and high temperature. This has happened during testing of Tesla electric vehicles. When this occurs it can lead to loss of life, property damage, and several thousand recalls which results in massive financial loss (Wei, 2011).

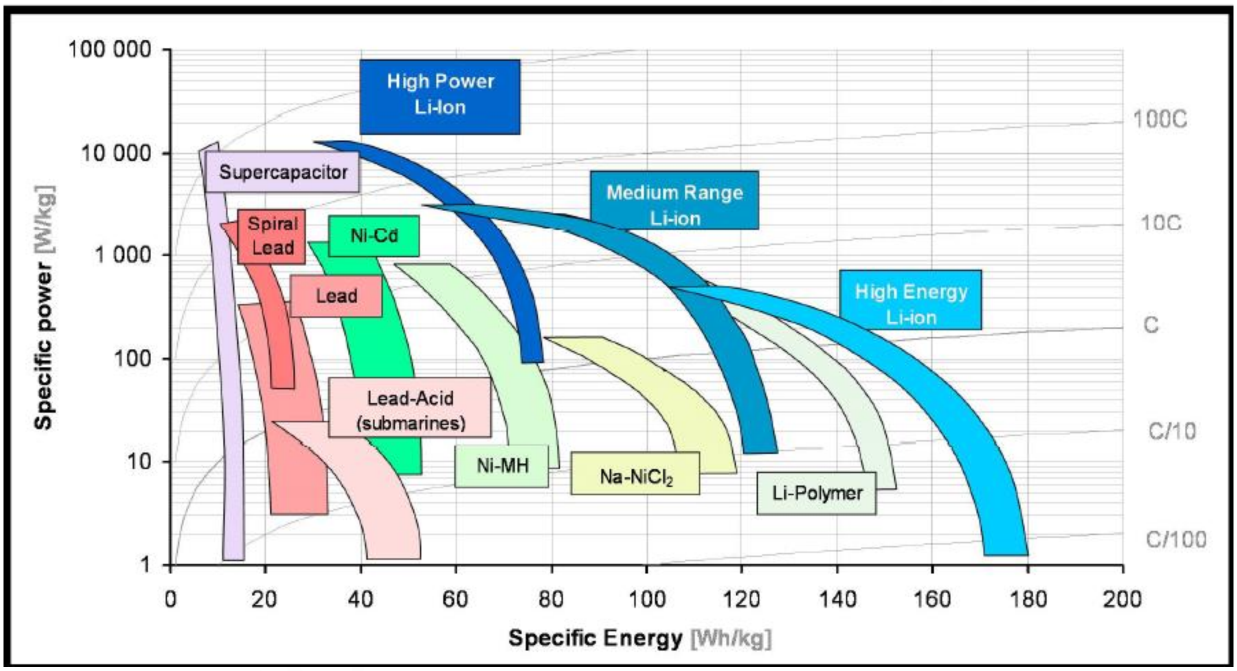

Figure 1 Ragone plot comparing several types of cell chemistries and other energy storage devices (Kalhammer, 2007).

2. RELATED WORKS

Peng, (2017) conducted equalization experiment using four Lithium cells connected in series, with initial SOC of 39.5%, 30%, 30% and 20%. In order to supply power to the cells, the researcher supplied 10A current to charge the four series batteries to the extent that the SOC of the battery pack rose to 80% and then the charging was stopped. The balancing experiment was with respect to SOC of the highest battery in series. Results showed that, at equilibrium process, SOC of each cell was 80%, 79%, 79% and 69.5% respectively after 181min. Andrea *et al* (2019) employed nonlinear model predictive strategy to determine characteristics of output of series connected cells when current was injected into it. LIONSIMBA simulator was the programming software used in the experiment. According to the researcher, when current is forced through cells of different capacities, there is high probability that different values of SOC would be recorded at the end of the charging process, which could be amplified over time. The researcher also revealed that the output characteristics were nonlinear in nature. Results further showed that current has huge impact on the internal temperature of the cell as temperature increases with increase in current. Results also showed that voltage increase with time. Experiment was carried out in 2000sec. The author also stated that charging of each cell was interrupted as soon as the threshold was hit. in order to determine relationship between current and temperature. Mizanur *et al*. (2016) used charging current of 1-4Amp with a range of ambient temperature between 25^0C-40^0C and SOC difference of 5% in the experiment using Matlab/Simulink software. It was discovered that ambient temperature and current flowing through the cells increased internal

temperature of the cells. Simulation time for the experiment was 5000sec, ultimately, increased in current led to increase in temperature.

2.1. Li-ionVs Other Cell Chemistries

Though the researcher's interest is LIBs, comparison with other cell types will be made. This is shown in Ragone plot in Figure 1 (Kalhammer, 2007). From the figure, lithium ion chemistries outperform other cell chemistries in energy density per kg.

2.2. Types ofLIBs

LIBs are generally classified based on their cathode materials. Table 1.0 shows the list of LIBs family based on their chemical materials, its features and applications. In the case of lithium titanate technology, the anode is made of titanate material.

Table 1: Types of lithium ion batteries and the features (Battery University, 2013)

<table>
<tr><th>Chemical technology</th><th>applications</th><th>features</th></tr>
<tr><td>Lithium Cobalt Oxide (LCO)</td><td>Cell phones, cameras and laptops</td><td>High capacity but less safe</td></tr>
<tr><td>Lithium Manganese Oxide (LMO)</td><td rowspan="4">Electrical bi-cycles, electrical vehicles (EV)</td><td rowspan="4">Lower capacity but higher specific power and long life, most safe</td></tr>
<tr><td>Lithium Iron Phosphate (LFP)</td></tr>
<tr><td>Lithium Nickel Manganese Cobalt Oxide (NMC)</td></tr>
<tr><td>Lithium Nickel Cobalt Aluminium Oxide (NCA)</td></tr>
<tr><td>Lithium Titanate (LT)</td><td>Automotive,electrical grid,power train,bus</td><td>High output voltage, short charging time, long life and safe.</td></tr>
</table>

However the focus of this paper is on Li-Ion Phsosphate chemistry.

2.3. Battery Parameters

Li-ion batteries come with voltage specification from the manufacturers; most times, the imprinted voltage is the nominal voltage. Most lithium batteries/cells are rated 3.6V.The implication of the nominal voltage supply of a battery/cell is that its voltage supply under different load conditions may vary towards an upper and lower limit. Battery voltage increases with increase in system temperature implying that temperature has a great effect on the battery. This relationship is illustrated through Nernst equation.

$$\mathrm{Vu,i} = \mathrm{Uo} + \frac{\mathrm{RT}}{nF}\mathrm{In}\left(\frac{\mathrm{\gamma\beta,i}x\beta,i}{\mathrm{\gamma\alpha,i}x\alpha,i}\right) \qquad 4.0$$

Or equivalently,

$$\mathrm{Vu,i} = \mathrm{Uo} + \frac{\mathrm{RT}}{nF}\mathrm{In}\left(\frac{x\beta,i}{x\alpha,i}\right) + \frac{\mathrm{RT}}{nF}\mathrm{In}\left(\frac{\mathrm{\gamma\beta},i}{\mathrm{\gamma\alpha,i}}\right) \qquad 5.0$$

Where i refers to the electrode (n for negative or p for positive), Uo is a reference potential, R is universal gas constant, T is electrode temperature, n is number of electrons transferred in the reaction ($n = Li - ion$), F is Faradays's constant, x is mole fraction, where α refers to lithium intercalated host material, β is unoccupied host material and γ is activity coefficient (Karthikeyan *et al* 2008).

2.3.1. Cut-off Voltage

Cut-off voltage is defined as the lowest allowable voltage. This voltage generally defines the "empty" state of the battery (MIT Electric Vehicle Team, 2008). It is not advisable to discharge the battery below the cut off voltage level; otherwise partial capacity of li-ion battery will be lost permanently.

2.3.2. Open Circuit Voltage (OCV)

It is defined as voltage across battery terminals with no load applied. The open-circuit voltage depends on the battery SOC, increasing with SOC (MIT Electric Vehicle Team, 2008). It defines potential difference on no load condition.

2.3.3. Battery Capacity

Coulomb describes the time a battery can produce a given current. The Coulomb is the unit of electric charge corresponding to one ampere-second (As) (Shen, 2010). In practice, however, cell battery capacity is more commonly expressed in Ampere-hour (Ah) or mili ampere-hour (mAh). Batteries' capacity depends on the active material, size and thickness of the plates, electrolyte density and thickness of the separators. A battery capacity is usually expressed as the product of twenty hours and how much current that a new battery can consistently supply for twenty hours while remaining above a specified terminal voltage (Abdurrahman, 2012). For instance, a battery rated at 100 Ah can deliver 5A at room temperature for 20 hours.

2.3.4. Li-ion battery Discharge and Charge Characteristics

The charging and discharging processes are logarithmic function. A plot of voltage and rate capacity is as shown in figure 2 and the voltage values range from 2.8 to 4.3 at capacity rate from 20 percent to 120 percent.

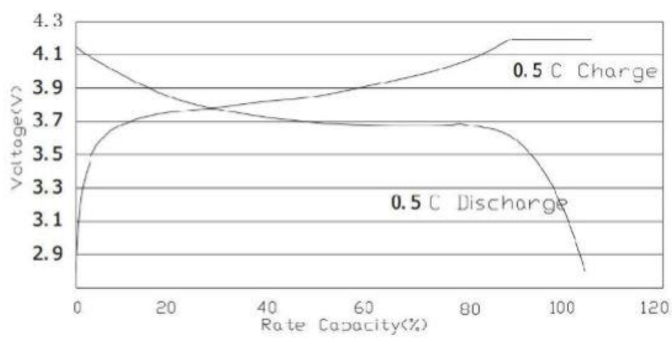

Figure 2: Charge and discharge characteristics of li-ion battery (Alldatasheet, 2017)

2.4. Problems of Battery Imbalance

Battery pack is as good as the weakest cell. The weakest cell determines the pack's performance and capacity if the pack is working in an unbalanced status. This is similar to Canninkin law, which postulates that the amount of wine that a cast can hold is determined by the shortest board. With the imbalance situation, the battery pack would not be fully charged and cannot completely discharge to the cut-off voltages. Due to this, the available capacity will be reduced. During constant current charging process, the weak cells reach the predetermined cut off voltage before other cells. Other cells still require charge at this point but in order to prevent overcharging of one cell, the whole pack switches to constant voltage charging mode. Also, during discharge process the weakest cell (s) reach the low cut off voltage before other cells. At this point the discharging will cease whereas other cells are available to deliver more energy thus resulting in reduced runtime and efficiency.

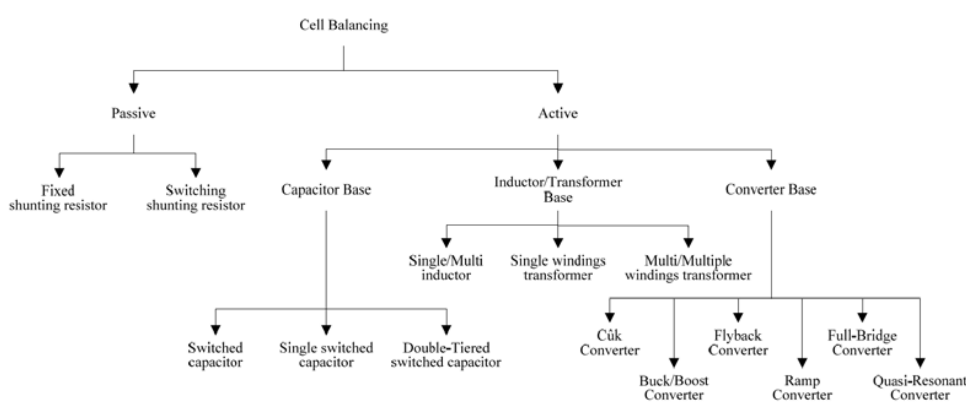

Figure 3: Balancing Techniques (Daowd et al, 2014)

2.5. Cell Balancing Technology

A battery pack that is made up with multiple batteries connected in series is utilized to provide enough output voltage to power the external devices (Zhang, 2016). In series connection, the same current flows through all the cells in the pack for both charging and discharging process. Notwithstanding this behavior, all the battery cells do not have similar performance. There always exist more or

less practical differences, such as internal resistance, internal chemical variations, numbers of cycling, temperature effects and so on (Chen et al 2006; Lindemark, 1991). Battery imbalance in a multiple cell pack will lead to critical problems in battery performance. For example, in a 12 cell battery pack that supplies 48 volts, it is expected that each cell will provide identical voltage of 4 volts under ideal situation. This does not happen in real life due to the imperfection of manufacturing process and environmental effects. Normally, the difference in capacity among cells does not exceed three percent for a well-balanced pack. Figure 3 shows the different balancing techniques.

2.6. Battery Management System

Battery management system (BMS) of li-ion battery pack can be achieved using different approaches with each having its own strengths and weaknesses. Due to continuous electrochemical reactions going on in all the cells/batteries in the pack, there is need for an external system that will monitor, control, give user feedback and ensure they are operating within acceptable range. A regular charger that looks at the battery pack as a whole will not be able to handle this. The voltage, temperature and current across the individual cells will be monitored and controlled by BMS as the need arises. In order to fulfill the objectives of BMS, the following functions have to be accomplished:

1. Prevent exceeding or falling below the set voltage or temperature limits of any cell. This is done by directly stopping the charging current or giving the charger instruction through a logic controller. By doing this, thermal runaway and explosion is mitigated. In order to control the temperature, there is need to stop battery current directly by adjusting charging current of triggering external cooling device if integrated in BMS.
2. Prevent the charging or discharging current of the cell from exceeding its limit.BMS can also balance the cells/batteries to maximize its capacity. This can be achieved by draining charge from the most of the charged cell until its voltage is low enough so that the charger can be applied again and charge the other cells or by moving power from the most charged cells to lower charged cells. This is done repeatedly till a balance is achieved in the SOC. Once this is achieved, charging can continue till all the cells reach 100% charge. BMS is also needed during the discharge of li-ion batteries so that the load is thrown off as soon as any cell reach the low cut off voltage. Discharging lithium battery beyond this level will result in permanent failure due to the formation of dendrite across the two electrodes. A dendrite is a kind of electrical short.

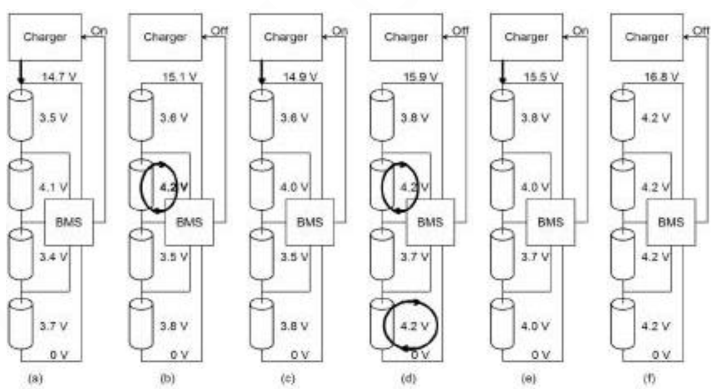

Figure 4: Charging with BMS controlling the charger: (a) charging, (b) charging stops when any cell reaches cutoff voltage, (c) charging restarts after cell's voltage is slightly reduced by balancing and (d) the process repeats until the pack is balanced as in e & f (Andrea, 2010).

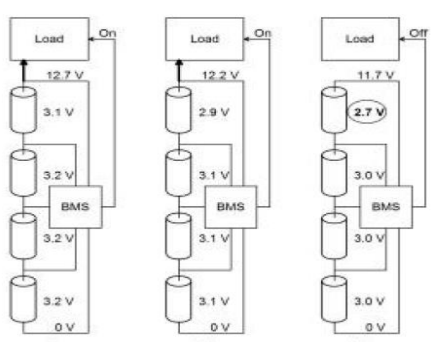

Figure 5: Discharging with BMS controlling the charger (a) discharging, (b) discharging and (c) discharging stops when any cell drops to the bottom cutoff voltage (Andrea, 2010)

2.7. Balancing Techniques

The balancing methods can be classified as passive balancing and active balancing. Passive balancing method removes the charge from the fully charged cells or higher voltage cells through the dissipated resistors to match the charge in those cells that have lower charge. Active cell balancing transfers the charge from the higher cells to lower cells or delivers more charge to those lower charge cells (Daowd et al, 2011). It has 20 different topologies according to the component it chooses. It can be simply separated as capacitor based, inductor/ transformer based and converter based. For the capacitor based, it can be classified by the switched capacitor, single switched capacitor, and double-tied switched capacitor based on the switches it uses. In the case of inductor and transformer based active balancing method, it can be divided as single/ multi inductor, single winding transformer and multiple windings transformer. For the converter based method, it can be divided as cuk converter, buck-boost converter, fly back converter, full bridge converter and Quasi-Resonant converter. Some of them may have some overlap, just like the fly back converter, active balancing method may also be treated as the transformer based method.

2.8. BMS Topologies

The structure of BMS depends on the operating requirements of the battery pack/bank. There are three basic topologies in battery management system. They are:

1.Centralized Topology
2.Distributed Topology
3.Modular Topology

2.8.1. Centralized Topology

Here, each of the cells in the battery pack/bank is connected directly to the master controller. For N number of cells, an N+1 number of cables are used for the connection. This scheme is easy and cheap to implement.

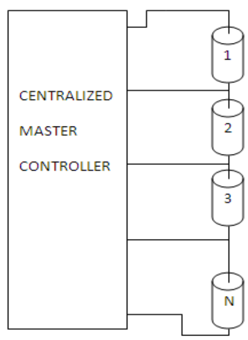

Figure 6: Centralized topology

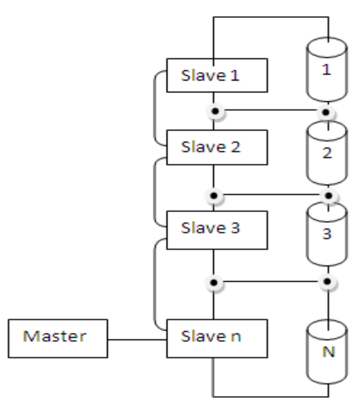

Figure 7: Distributed topology

2.8.2. Distributed Topology

In this topology, voltage monitors and discharge balancers, which can turn off the charging device and can report its status, along with digital communication devices are connected in parallel with each cell. Simplicity and reliability are the major advantages of this topology. There will be N modules for N cells plus one master module controlling the slaves. Communication runs over a dedicated communication wire, typically a daisy-chain connecting all slaves with the master. This solution requires 2N voltage measurement wires for N cells as well as N communication wires.

2.8.3. Modular Topology

In the modular structure, a few cells are controlled by a single slave controller and each of these slave controllers communicates with the master controller. No printed tiny circuit boards are needed in this type of arrangement (Agnivesh, 2016).

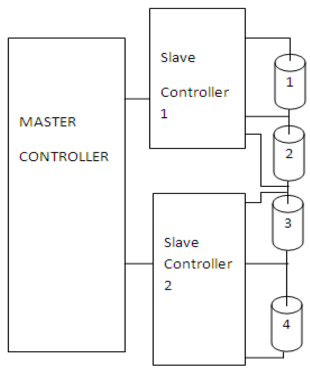

Figure 8: Modular Topology

2.9. Voltage Sensing

Li-ion cells have a normal operating range of 3.0V to 4.2V which is within the microcontrollers A/D conversion range of 0 to 5V. The voltage signal can still be conditioned such that the cells' voltage will not damage the microcontroller even if it rises so high. The voltage of the series connected cells has to be measured individually to eliminate the possibility of overcharging. Microcontroller chips can be effectively used to measure the voltage of a battery using some necessary procedures and taking note of some vital precautions (Texas Instruments, 2018).

2.10. Current Sensing Methods

There are different methods of measuring current.

2.10.1. Sense Resistors

In order to sense current, there is need to connect a resistor in the current path. In some cases, the resistor can be connected in series with an inductor, and the load. Since current values in li-ion batteries are high (in the order of amperes), even a small resistor can cause severe power losses and reduce the efficiency by 2% to 10%, hence, the measurement is done for a few seconds. The value of the sense resistor cannot be reduced to negligible values, since the accuracy of the detection reduces as the voltage drop across the resistor degrades, which is mainly caused by offset, noise, and high gain-bandwidth requirement. The sense resistor offers the lowest cost and most accurate solution to low current measurement requirements where the measured current is less than three amperes (DST Solar, 2014).

2.10.2. Mosfet-Rds

When MOSFETs is in 'ON' state, it functions as resistors and are biased in the Ohmic (non-saturated) region. When MOSFETs is used as switches with small drain source voltage, the equivalent resistance of the device is as shown in equation 7.0.

$$Rds = \frac{L}{uCox\frac{W}{L}(Vgs-Vt)} \qquad 7.0$$

where $\mu(m^2/(V.s))$ is the mobility; $C_{ox}(A/W)$ is the oxide capacitance per unit area; $L(m)$ and $W(m)$ are the MOSFET length and width; and $Vt(V)$ is the threshold voltage. Consequently, current is the battery can be estimated bysensing the voltage across the drain-

source of the MOSFET, if *Rds*of the MOSFET is known. Low accuracy and switching noise from non-zero gate currents during transients are the major disadvantage of this technique (Preeti, 2012).

2.10.3. Hall-effect Sensors

Hall-effect sensors are among the popularsolutions for current measurements. Current in a conductor produces a magnetic field around it, when a second current-carrying conductor is placed into the magnetic field; the electrons are pushed to one side of the second conductor more than the other side, which generates a voltage across its width. This voltage across increases as the magneticfield value increases, which also increases with current flowing into the first converter. This phenomenon is known as the Hall effect. Discrete Hall-effect sensors use ferromagnetic condensers to increase sensitivity. Generally, the sensitivity of the Hall-effect sensor in CMOS is very low even with additional micromachining steps to add ferromagnetic material for condensers. Current sensing can also be broadly classified into two types; low side and high side sensing.

2.10.4. Low Side Current Sensing

This method senses current that flows in the return path of the power that is connected to the monitored load, this method is effective because current is uni-directional (flows in only one direction).

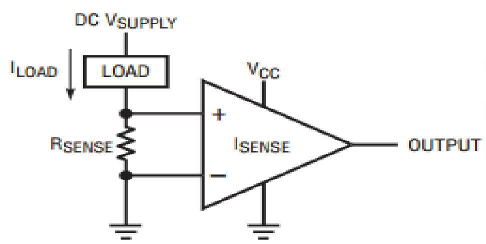

Figure 9: low side sensing configuration (Texas Instrument, 2017)

Where I_{LOAD} is load current (A), R_{SENSE} is resistance of the sense resistor (ohm), V_{CC} is voltage common collector (V), I_{SENSE} is current across the sense resistor (A)

Low side sensing advantages

- Low input common mode voltage
- Ground referenced output voltage
- Easy single supply design

Low side disadvantages

- Load lifted fromdirect ground connection
- Load activated by accidental short at ground end load switch
- High load current caused byshort is not detected

Amplifier types for low side implementation

- Precision zero-drift op amps: LTC2050, LTC2054
- Instrumentation amplifiers:LTC2053, LT1990, LTC6943
- Rail-to-Rail Input op amps: LT1677

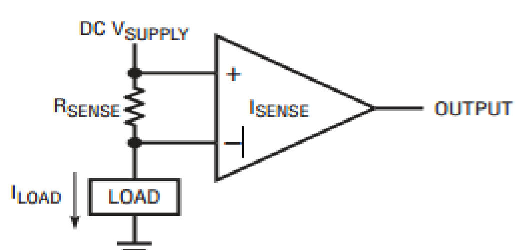

Figure 10: High side sensing configuration (Linear Technology Corporation, 2017)

2.11. High Side Current Sensing

This method senses current in the supply path of the power connected to the monitored loadCurrent sensed in the supply path of the powerconnection to the monitored load. Flow of current is normally uni-directional.

Where I_{LOAD} is load current (A), R_{SENSE} is resistance of the sense resistor (ohm),$V_{CC}$is voltage common collector (V), I_{SENSE} is current across the sense resistor (A)

High side advantages

- Load is grounded
- Load not activated by accidental short at power connection
- High load current caused byshort is detected

High side disadvantages

- High input common mode voltages (often veryhigh)
- Output needs to be level shifted down to system operating voltage levels

Amplifier types for high side implementation

- Dedicated current sensing amplifiers: LT6100, LTC6101, LT1787
- Over-the-Top™ op amps: LT1637
- Flying capacitor amplifier: LTC6943 .

3. DETERMINATION OF CHARGING AND DISCHARGING RATES OF LI-ION BATTERIES

It is the discharge or charge current rate in amperes, numerically equal to rated capacity of a cell in ampere hours, rated at the 1hour discharge rate. A cell will deliver its nominal capacity for one hour when discharging at the C rate (Venkataramanan *et al*, 2002). It is expressed in Ampere or multiples of C rates. The real time C rate (discharging or charging current) of a battery is given by 5% (1/20) of the battery capacity for the best operational efficiency. For instance, battery with rating of 100Ah can deliver 5A for twenty hours (1/20 C rate). If the battery discharges at a lower rate, it would run longer before been discharged. In reality, the relationship between battery capacity and discharge is nonlinear in nature (Roger 2019). Batteries can be charged or discharged at n multiples of its C rate that is 1C, 2C, 0.5C, 0.1C which implies that its charging /discharging rate of 1 hour, 30 minutes, 2 hours, 10 hours respectively for a 100Ah battery and the runtime varies for different capacities of batteries which can be estimated from their rated values. This parameter is essential when battery backup systems are to be designed (inverters, solar systems and industrial battery driven loads) as it directly affects the performance, durability, and life span of the battery. With an increase in discharge rate, the battery run time is reduced as proven by Peukert's equation.

3.1. Effect of Peurkert's equation on amp-hour (Ah) rating of battery

Peukert's equation is a suitable way of characterizing cell behavior and quantifying the capacity offset in mathematical terms. It is an empirical formula which estimates how the rate of discharge affects battery available capacity. For one ampere discharge rate Peukert equation is stated in equation 8.0

$$C = I^{k} T \qquad 8.0$$

Where C is rated in amp hour (Ah). This is the theoretical capacity of the battery, I iscurrent drawn, T is time, and k is Peukert's number, which is constantfor a given battery. According to equation 3.1, with less energy available in the battery, high current will be drawn. It further expresses direct relationship between Peukert's number and the internal resistance of the battery. Peukert's equation does not just describe an empirical system; it has practical relevance in estimating effective current capacity (Ah) under different current loads. For instance, when a battery of 100 Ah rating discharges at a rate that fully drains the battery in 20 hours(which is the conventional rating standard used by battery manufacturers, that is discharging at 5% of its capacity) but the same battery discharged at 20 amps will not last 5 hours but will only last about 3 hours and 30 minutes. This implies that a battery delivers lower capacity/power when discharged with a higher current. Another form of expressing

Peukert's equation is given as

$$t = H\left(\frac{C}{IH}\right)^{k} \qquad 9.0$$

Where: H is rated time (hours), C is rated capacity at that discharge rate (ah), I is real discharge current (Amp), k is Peukert's constant (dimensionless), t is real time taken to discharge the battery (in hours) .Peukert's law can be rewritten as

$$It = C(C)^{k-1}\, IH \qquad 10.0$$

Solving for It, which is the real capacity at the discharge rate of I. A battery's performance under continuous heavy currents can be deduced from the value of Peukert's number. The battery performs well when the value is close to 1. The higher the number, the more lossa battery will have when discharged at high currents. Different batteries have different Peukert's constant. Range of K values and their applications is shown in table 2.0

Table 2: Range of K values and their applications

K-Value range	Applications
1.05 - 1.15	AGM batteries (automotive and renewable energy systems)
1.1-1.25	Gel batteries (renewable energy systems
1.2-1.6	flooded batteries (automotive industry and few renewable energy storage systems)

A deep cycle battery with rated capacity of 200Ah, its discharge/recharge rate (C rate) is 5% of its capacity.

Therefore, 5% of 200Ah =10Ah

Battery Runtime =200Ah/10Ah=20hours

When a user decides to discharge this battery at the rate of 20A; from the linear relationship the battery should last for 10 hours, but this is usually not the case.
This scenario can be explained using Peukert's equation.

$$It = C\left(\frac{C}{IH}\right)^{k-1} \qquad 11.0$$

Where C =200Ah

I=20A, H=20 hours,k =1.25 for a gel battery It =200(200/20X20) ^1.25-1

It =200(0.5) ^0.25
It =168.18Ah

Therefore, 168.18Ah is the effective rating and at the discharge rate of 20A, Runtime=168.18Ah/20A=8 hours 24 minutes.

Table 3: Relationship between run time, effective capacity and discharge rate of 200Ah battery with Peukert's exponent of 1.25

Discharge rate (A)	C (Ah)	H (hours)	IH	C/IH	(C/IH)^0.25	Effective Capacity AmpH	Runtime (hrs)
0.5	200	20	10	20	2.114743	422.9485	845.897
1	200	20	20	10	1.778279	355.6559	355.6559
5	200	20	100	2	1.189279	237.8414	47.56828
10	200	20	200	1	1	200	20
15	200	20	300	0.666667	0.903602	180.7204	12.04803
20	200	20	400	0.5	0.840896	168.1793	8.408964
25	200	20	500	0.4	0.795271	159.0541	6.362166
30	200	20	600	0.333333	0.759836	151.9671	5.065571

35	200	20	700	0.285714	0.73111	146.2221	4.177774
40	200	20	800	0.25	0.707107	141.4214	3.535534
45	200	20	900	0.222222	0.686589	137.3178	3.051507
50	200	20	1000	0.2	0.66874	133.7481	2.674961

4. RESULTS AND DISCUSSION

Implication of Peukert effect on real batteries isas shown in table 3.0. It can be deduced that as current approaches a very low level, the real capacity of the battery appreciates considerably beyond the rated battery capacity, thus making it not exactly like Peukert's equation. Peukert's equation does not apply at low level discharge rates. On the contrary, when this behavior is balanced with self-discharge of the battery, the effect of the appreciated capacity is cancelled. From table 3.0, a 200Ah battery discharged at the rate of 1A will last for 355 days 39 minutes which is about 15 days; during this time, a typical deep cycle would have self-discharged 15 to 20 amperes. Therefore, Peukert's effect is veritable at all discharge rates of a battery (high and low levels). Peukert's effect is partially a result of slow electrolyte diffusion and partially a result of an internal resistance that varies as a function of discharge rate. This makes the calculation and measurement of battery parameters more intricate and convoluted for most SOC meter designers.

5. CONCLUSION

This work carried out a comprehensive study on optimizing li-ion Battery Management System (BMS). Various literatures were reviewed in carrying out this research and Peukert effect is used to carry out both the charging and discharging rate of li-ion batteries. From the investigation, the effect of Peukert's constant is that discharging at lower rates increase run time substantially. For instance, a 200Ah (at the 20-hour rate), with Peukert's exponent of 1.25, discharging the battery at 10A will last for 20 hours, the same battery will last for 8 hours 32 minutes at a 20A discharge rate and 3 hours 24 minutes at a discharge rate of 40A.

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